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PRELIMINARY ANALYSIS OF PERFORMANCE AND LOADS DATA FROM THE 2-MEGAWATT MOD-1 WIND TURBINE GENERATOR

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ABSTRACT

The DOE/NASA Mod-1 wind turbine generator installed on Howard's Knob near Boone, North Carolina, was dedicated on July 11, 1979. With a rated power of 2 MW and a rotor diameter of 61 meters, the Mod-1 is the largest wind turbine ever constructed. Initial operation during August, September, and October of 1979 has produced preliminary test data on output power versus wind speed, rotor blade loads, system dynamic behavior, and start/stop characteristics. These data have been analyzed statistically and are compared with design predictions of system performance and loads.

To date, the Mod-1 wind turbine generator has produced up to 1.5 MW of power, with a measured power versus wind speed curve which agrees closely with design. Blade loads have been measured at wind speeds up to 14 m/s and also during rapid shutdowns. Peak transient loads during the most severe shutdowns are less than the design limit loads. On the inboard blade sections, fatigue loads are approximately equal to the design cyclic loads. On the outboard blade sections, however, measured cyclic loads are significantly larger than design values, but they do not appear to exceed fatigue allowable loads as yet. The causes of these higher loads and their effect on long-time fatigue life are still being determined.

INTRODUCTION

According to current forecasts, the economic conversion of wind energy to electricity by electric utilities will very likely involve large clusters of megawatt power horizontal-axis wind turbine generators, each sweeping an area of 2000 to 10,000 square meters. However, prior experience with large megawatt-size wind systems in the United States is limited to that obtained almost 40 years ago with the 1.25 MW Smith-Putnam machine. That wind turbine was operated for about 1000 hours between 1941 and 1945 (ref. 1). Therefore, the Department of Energy (DOE) is sponsoring the Mod-1 Project for the purpose of gaining current experience in the design, construction, and operation of a megawatt-size wind turbine generator at an electric utility site.

Objective

The objective of this report is to present the results of the first operational tests of the Mod-1 wind turbine generator, together with a preliminary assessment of the power it produces and the loads it sustains. These tests are quite recent and the test data are very limited in scope, so the conclusions drawn in this report must be considered as tentative. However, these data will serve to describe the present status of the machine and the type of information upon which a later, more detailed assessment will be made.

Mod-1 Project Overview

In addition to DOE, the major participants in the Mod-1 Project are the Lewis Research Center of the National Aeronautics and Space Administration (NASA), which is managing the project; the Space Division of the General Electric Company (GE), which is the prime contractor; and the Blue Ridge Electric Membership Co., (BREMCO), which is the operator. Work on the project began in July, 1976, and the Mod-1 wind turbine generator was dedicated three years later, on July 11, 1979. The site selected by DOE for the machine is a hill overlooking Boone, North Carolina, called Howard's Knob. At the present time, GE is conducting acceptance tests which are being monitored by NASA. Following these tests, the Mod-1 system will be operated by BREMCO as an integral part of the utility's system. This is scheduled to take place in the first quarter of 1980.

Planned Technical Assessments

Three technical assessments are planned for the Mod-1 Project in order to evaluate (1) machine performance, (2) interfacing between the machine and the utility, and (3) effects of the machine on the environment. The machine performance assessment is being conducted by NASA and covers design procedures, power and energy output, loads and stresses, vibrations and deflections, aeromechanical stability, and reliability.

The assessment of the interface between the Mod-1 as a generating station and the BREMCO utility will be conducted by an electrical systems consultant to be selected by DOE and NASA. A previous assessment of this type was conducted on the 200 kW Mod-OA wind turbine generator in Clayton, New Mexico, and is reported in Reference 2. Plant characteristics such as system stability, and operating and maintenance costs, as well as effects on planning and operations will be evaluated. Environmental effects of the Mod-1 wind turbine will be assessed by the Solar Energy Research Institute (SERI) of Golden, Colorado. Wildlife hazards, TV and RF signal interference, and public acceptance will be studied.

SYSTEM DESCRIPTION

Figure 1 is a general view of the Mod-1 wind turbine generator with its ground support equipment on the Howard's Knob site (elev. 1347 meters). The Mod-1 system and its primary components are described in detail in References 3 and 4, and only a summary will be given here. As shown in Figure 1, the Mod-1 is a large, two-bladed, horizontal-axis wind turbine supported on a truss tower. Power generation equipment is enclosed in a rectangular nacelle atop the tower, and a control room and transformer are on the ground, within the tower base. While the fenced area around the machine is relatively small (less than 800 square meters), it provides sufficient space for an office trailer next to the tower and a NASA van containing data recording and processing equipment.

The Mod-1 rotor blades measure 60.7 meters, tip-to-tip, operate downwind of the tower, and sweep an area of 2820 square meters at a speed of 34.7 rpm. Blade spars are welded steel and the trailing edges are thin stainless steel bonded to foam cores. Rotor speed and power are controlled by pitching the blades at the hub, from the feathered or stopped position shown in Figure 1 through an angle of approximately 90 degrees to the full-power position. The rated power of the 1800 rpm AC synchronous generator is 2.0 MW. The tower height, from the four foundation blocks anchored into bedrock to the rotor shaft, is 42.7 meters.

On the basis of rated power and rotor swept area, the Mod-1 wind turbine generator is the largest wind-driven machine ever built. Total weight of all components (excluding the foundation) is 317,000 kilograms, which is distributed among the various assemblies as listed in Table I.

The layout of the equipment in the nacelle is shown schematically in Figure 2. The complete power train, from hub to generator, was assembled on the bedplate for run-in tests at a GE plant in Philadelphia. An auxilliary drive motor was mounted above the pitch-change actuators and temporarily connected to the high speed shaft in the gearbox in order to rotate the power train at nearly synchronous speed. During this ground testing, the bedplate was supported on the yaw drive assembly and the top section of the tower.

Following the run-in tests in Philadelphia, the nacelle equipment was disassembled for shipment to Howard's Knob and then reassembled, component by component, on top of the tower. Two cranes were used to lift the equipment. The heavy weights and the tower height precluded the "single lift procedure used successfully for smaller DOE/NASA machines (ref. 5). The feasibility and economy of the component-by-component method for megawatt-size wind turbines was verified in the construction of the Mod-1.

RESULTS AND DISCUSSION

Power Output

The performance of the Mod-1 wind turbine generator, in terms of power output versus wind speed, is shown graphically in Figure 3. The system is designed to generate power at wind speeds above 7 meters per second, as measured at hub height. Rated power of 2.0 MW is produced at wind speeds above 16 meters per second. When the wind exceeds 20 meters per second the machine is shut down, to avoid overstressing the blades. At the hub elevation of 1390 meters the standard air density is 14 percent less than at sea level, and this effect is included in the design performance curve.

The test data shown in Figure 3 represent approximately one hour of operation on October 5, with the Mod-1 generator connected to the BREMCO system. Continuous records of electrical power and free stream wind speed were analyzed statistically to obtain the data points in this figure. Free stream wind speed was measured by an anemometer at hub height on a meteorological tower 93 meters from the machine. Average power output and average free stream wind speed were calculated for each rotor revolution, a period of approximately two seconds.

As the 50th percentile points on Figure 3 indicate, median measured power output is very close to the design output. Negative power occurs when the generator is "motoring" during low winds.

The spread between the 16th and 84th percentiles is typical of the variability present when a single anemometer is used to indicate wind speeds across a large rotor disk.

The preliminary power data shown in Figure 3 verify the design cut-in wind speed of 7 meters per second and indicate that power generation at higher wind speeds will be very close to design values.

System Vibration

Wind turbines, like all flexible structures, tend to vibrate in preferential patterns, or modes, each with its own frequency. To avoid resonances and load amplification, component masses and stiffnesses are adjusted during the design phase so that modal frequencies do not coincide with certain integer multiples of the rotor speed. A typical example of the Mod-1 modal analysis performed by GE (ref. 3) is illustrated in Figure 4. This figure is a computer graphic display of the fourth mode of vibration of the Mod-1 structural system. Components are idealized in this model as a system of mass nodes and connecting stiffness links.

On the left side of the figure is the rotor and drive train subassemblies, on the upper right is the nacelle bedplate, and on the lower right is the truss tower. The arrows are displacement vectors indicating the direction and relative magnitude of deflections throughout the system during this mode of vibration. The predicted fourth mode frequency is 1.8 Hz or 3.1 times the rotor speed.

To assess the accuracy of the modal analysis, vibration tests were conducted on the Mod-1 structure, similar to testing reported in Reference 6. As noted in Figure 4, the measured frequency of the fourth or "tower lateral bending" mode was 2.1 Hz, about 17 percent higher than the design prediction. A total of ten modes with frequencies ranging from 0.3 Hz to 10 Hz were identified during the Mod-1 modal testing. All the important measured frequencies were within 20 percent of calculated values, which is within the accuracy required to avoid operating resonances. One possible explanation for the higher measured frequency in the fourth mode is the fact that the Mod-1 tower legs are fastened directly to bedrock, while the modal analysis assumed a more flexible foundation on soil.

While resonances at rated rotor speed can be avoided or minimized through design changes based on modal analysis, resonances at lower speeds during starting and stopping are often impossible to avoid. In this case, the objective of modal analysis is to prevent two such sub-rated resonances from occurring at the same time. This is done by requiring blade frequencies and tower frequencies to be separated.

Figure 5 illustrates a sub-rated resonance which occurs each time the Mod-1 wind turbine is started, at about 85% of its rated speed of 34.7 rpm. As shown on the lowest graph, two modes are excited as the speed increases with time. First, the blade's chordwise bending moment is excited when the rotor speed equals about 29 rpm. Second, tower bending is excited at a rotor speed of 32 rpm. These two modes are prevented from fully coupling by the 3 rpm speed separation. As shown in the middle and upper graphs, the increase in the cyclic chordwise bending moment near the blade root is limited to about 25 percent during the resonance. It may be inferred that the amplification of this load would be considerably greater were the blade and tower resonances to coincide. It appears that mode separation was successful in limiting the detrimental effects of an unavoidable resonance below rated rotor speed. No vibration or deflection problems have been identified in the system to date.

Blade Limit Loads

The largest Mod-1 blade loads, both by calculation and observation, occur during rapid feathering of the blades and stopping of the rotor from its overspeed limit of 39 revolutions per minute. Figure 6 shows a comparison between design loads for this condition and measured loads at three stations along the blades. The measured loads are the maxima of flatwise bending moments measured with strain gages while the blades were being feathered at a variety of rates. In the inboard half of the blade, the largest measured loads are less than the design limit loads. In the outboard regions of the blade, however, measured loads appear to equal or slightly exceed predicted limit loads. In general, the procedures for establishing limit loads have been verified by these test data.

Blade Fatigue Loads

In order to assess the fatigue design procedures used in the Mod-1 Project, a large sample of cyclic load data is needed, covering all wind speeds and directions in the operating range, starting and stopping transients, gustiness conditions, etc. To date only a small data sample has been recorded and analyzed. This sample consists of strain gage readings taken at four blade locations during 2800 rotor revolutions on October 5, 1979. During this sample, wind speeds ranged from 5 to 14 meters per second and the machine generated power from -0 2 to 1.6 MW. However, this small sample can be the basis of a preliminary comparison between design fatigue loads and measured loads when it is analyzed statistically as shown in Figure 7.

Figure 7 is a graph of a fatigue load factor versus the cumulative probability of occurrence of that factor. In this case the load factor is equal to the cyclic chordwise load (one-half the load range during each rotor revolution) divided by a nominal calculated cyclic load. The load calculation was made for a wind speed of 14.4 meters per second at hub height, utilizing a computer code called GETSS (General Electric Turbine System Synthesis), developed during the project (refs. 3 and 7). The design spectrum line on this graph represents a log normal distribution, with median value equal to the GETSS nominal case (load factor of unity) and a log standard deviation estimated from early tests on the Mod-O wind turbine at Plum Brook, Sandusky, Ohio.

The Mod-1 blades were designed for infinite life at chordwise loads which were 1.45 times the nominal GETSS case. As shown in the figure, the design loads were estimated to exceed observed loads over 99 percent of the time. The data taken on October 5 confirm this estimated load spectrum for wind speeds less than 14 meters per second, at an inboard blade station. No chordwise data are available yet at outboard stations or higher wind speeds.

Figure 8 shows cyclic flatwise load spectra at two inboard stations, 10 percent and 39 percent span. Here the log standard deviation is higher than it was for chordwise loads, again on the basis of early Mod-0 data, and the design load factor is 1.90. The test data spectra agree very well with the design spectrum, although there appears to be a tendency for load factors to be higher farther out along the blade.

This tendency is confirmed by cyclic flatwise loads measured at 75 percent span. As shown in Figure 9, measured load factors significantly exceed design load factors for equal probabilities of occurrence. These higher loads do not appear to exceed fatigue allowables yet, as shown in the figure. The causes of these higher loads in the outboard sections of the Mod-1 blades are still being studied and their affect on long-term fatigue life has not been evaluated.

PRELIMINARY CONCLUSIONS

On the basis of the first data on the Mod-1 wind turbine generator, the following preliminary conclusions can be drawn:

1. Power generation as a function of wind speed is very close to design.

2. No vibrations, deflection, or stability problems have been identified so far.

3. Maximum blade loads are less than design limit loads on inboard blade sections, and on outboard sections they are equal to or slightly in excess of design loads.

4. On inboard blade sections, measured fatigue load spectra agree well with design spectra, for wind speeds below 14 meters per second.

5. On the outboard blade sections, measured fatigue load spectra exceed design spectra, but appear to be within allowable fatigue loads.

REFERENCES

1. Putnam, Palmer Cosslett: Power from the Wind. Van Nostrand Co., New York, 1948.

2. Reddoch, T. W. and Klein, J. W.: No Ill Winds for New Mexico Utility. IEEE Spectrum, vol. 16, no. 3, Mar. 1979, pp. 57-61.

3. Mod-1 Wind Turbine Generator Analysis and Design Report. DOE/NASA/0058-79/2 - Vol. I, NASA CR-159495, May 1979.

4. Barchet, R. J.: Mod-1 Wind Turbine Generator Program. Proceedings, Third Wind Energy Workshop, 1977, Vol. 1, DOE CONF 770921-P1, pp. 76-91.

5. Thomas, R. L. and Richards, T. R.: ERDA/NASA 100 Kilowatt Mod-O Wind Turbine Operations and Performance. ERDA/NASA/1028-77/9, NASA TM-73825, 1977.

6. Linscott, B. S.; Shapton, W. R.; and Brown, D.: Tower and Rotor Blade Vibration Test Results for a 100-Kilowatt Wind Turbine. NASA TM-3426, 1976.

7. Spera, D. A.: Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines. DOE/NASA/1028-78/16, NASA TM-73773, 1977.

TABLE I

Weight Breakdown of the Mod-1 Wind Turbine Generator System

Assembly	Subassembly	Weight kg	Weight % of Total
Tower	Structure	139 700	44.1
	Cable, conduit	2 700	0.8
	Elevator, misc.	500	0.2
	Subtotal	142 900	45.1
Nacelle	Bedplate	30 400	9.6
	Gearbox	25 900	8.2
	Shafts, couplings, clutch	8 000	2.5
	Generator, exciter	6 200	2.0
	Fairing	2 200	0.7
	Lubrication, hydraulics	1 800	0.6
	Miscellaneous	1 800	0.6
	Subtotal	76 300	24.2
Rotor	Blades	18 800	5.9
	Bearings, supports	12 900	4.1
	Hub	6 700	2.1
	Pitch hydraulics	5 400	1.7
	Pitch mechanism	4 900	1.5
	Subtotal	48 700	15.3
Yaw	Bearing, support	21 000	6.6
	Drive motors	3 600	1.1
	Brakes	400	0.1
	Subtotal	25 000	7.8
Control	Enclosure, equipment	18 700	5.9
	Transformer	5 400	1.7
	Subtotal	24 100	7.6
TOTAL		317 000	100.0

Figure 1. - The 2.0 MW Mod-1 wind turbine generator installed on Howard's Knob near the city of Boone, North Carolina.

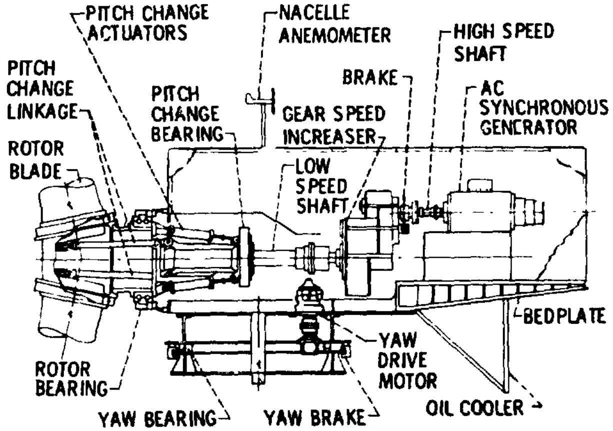

Figure 2. - Schematic diagram of the Mod-1 power train equipment.

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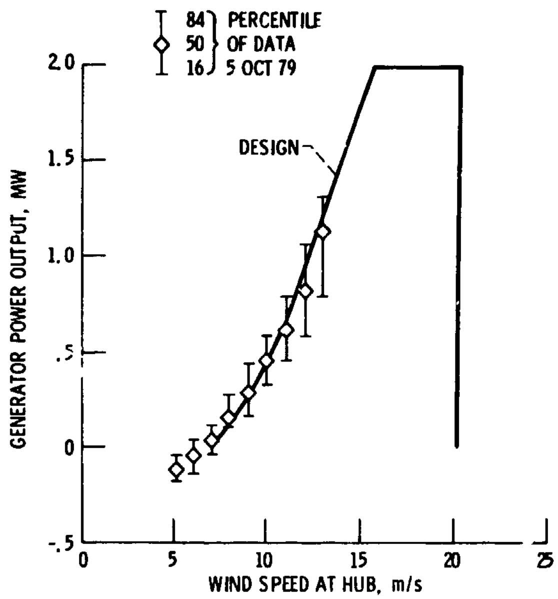

Figure 3. - Comparison of measured and design power outputs.

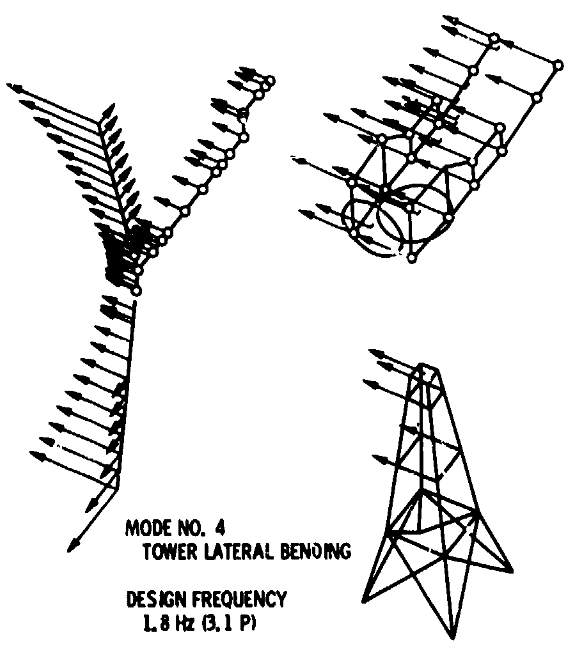

Figure 4. - Typical vibration mode of the Mod-1 structural system, and comparison of measured and design modal frequencies.

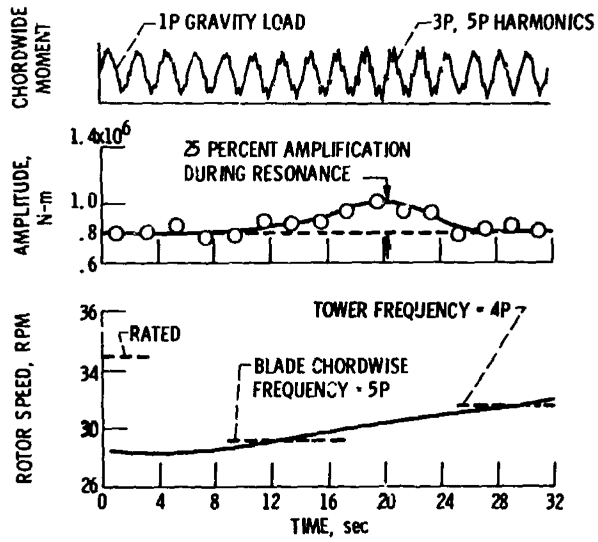

Figure 5. - Load amplification during startup of the Mod-1 wind turbine generator.

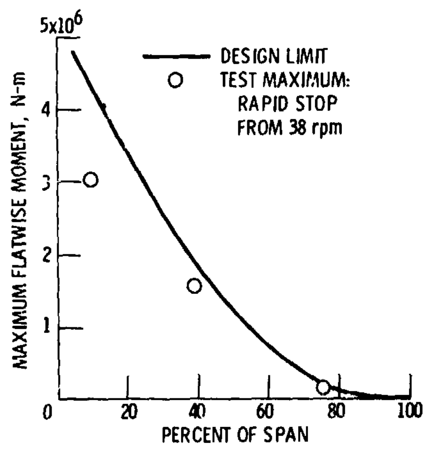

Figure 6. - Comparison of measured and design blade limit loads, in the flatwise direction.

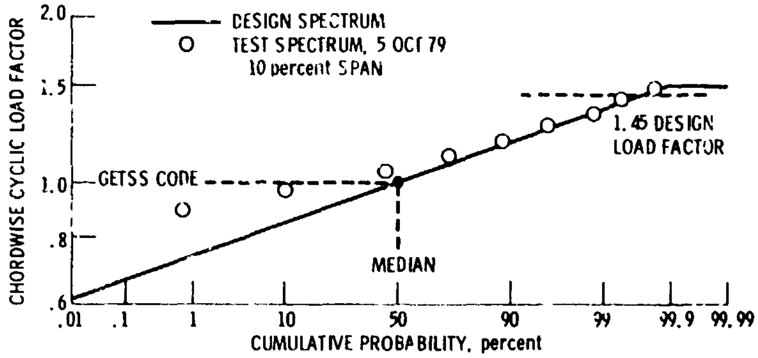

Figure 7. - Comparison of measured and design blade fatigue load spectra for inboard blade sections, in the chordwise direction.

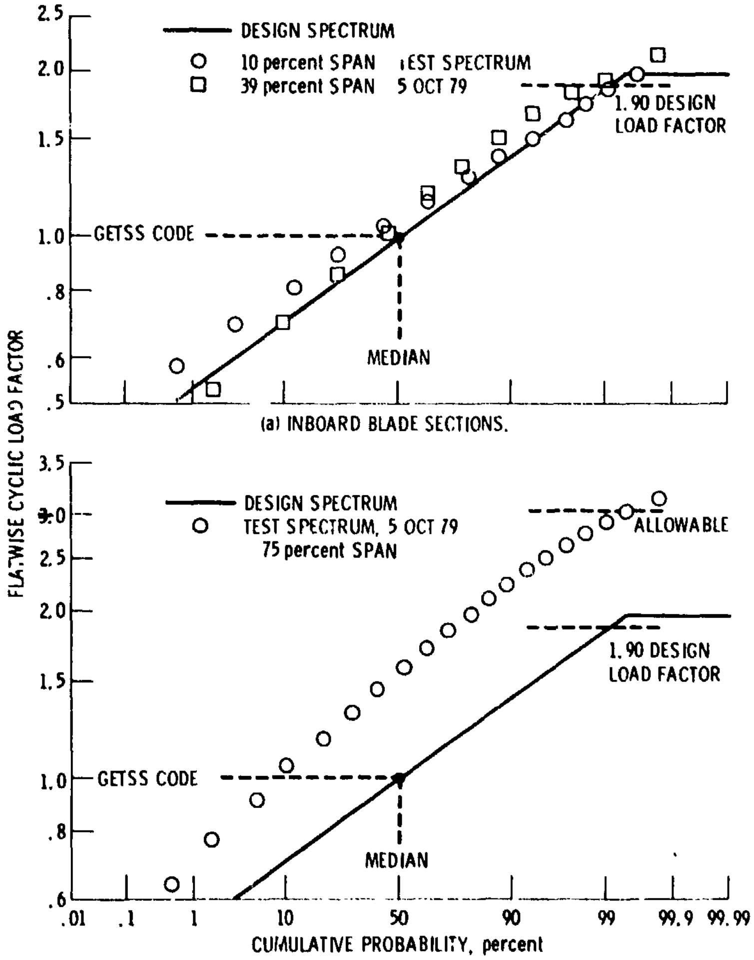

Figure 8. - Comparison of measured and design blade fatigue load spectra in the flatwise direction.